3D Printing - An Easy and Efficient Method to Fabricate High-Resolution 3D Printed Models for Medical and Educational Purposes

Assoc. Prof. Alexandru Ulici MD PhD[1,2], Eduard Liciu MD PhD[1,2,3], Adrian Dima MD[4], Beatrice Frumuseanu MD PhD[1], Maria Miruna Mihai[2,3], Asst. Prof. Roman Murzac PhD[3,5], Prof. Sebastian Ionescu MD PhD[2,6].

1. “Grigore Alexandrescu” Emergency Hospital for Children, Department of Pediatric Orthopedic Surgery, Bucharest, Romania
2. “Carol Davila” University of Medicine and Pharmacy, Bucharest, Romania
3. “The Romanian Medical Association of 3D Biomodelling” - AMRB 3D
4. Sanador Hospital, Bucharest, Romania
5. University Politehnica of Bucharest , Romania
6. “Maria Sklodowska Curie” Emergency Hospital for Children, Department of Pediatric Surgery, Bucharest, Romania

Corresponding Author: Eduard Liciu MD PhD

Abstract— The development of 3D printing techniques led to multiple types of materials that can be used in making medical models, including material that can be sterilized, thus facilitating the intraoperative manipulation of these devices by the surgical team.

We used 3D printed models for complex orthopaedic cases such as: scoliosis (idiopathic, congenital and neuromuscular), hip dysplasia, femoral osteosarcoma, pelvic trauma using especially Polylactic acid (PLA) and Polyether ether ketone (PEEK) through the means of fused deposition modelling (FDM) technology.

It was an elaborate process that involved a multidisciplinary team (an orthopaedic surgeon, a radiologist and an engineer) and that required a work protocol, in order to accomplish the optimal criteria that allowed surgical manoeuvres to be simulated on the resulted 3D printed models.

The purpose of this paper is to document and analyse the parameters used in biomodelling and to appreciate the impact of implementing 3D printed models in orthopaedy.

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Index Terms— 3D printing, 3D preoperative planning, biomaterials, orthopaedy, personalised treatment, PLA , simulated surgery.

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1 INTRODUCTION

Since the beginning, the 3D Printing Technology, also referred as additive manufacturing, managed to find its way in the medical field. At that time, the medical research segment was one of the few fields that afforded to exploit this new technology. Since 2009, when the price of a 3D printer went under 5000 $, becoming accessible to a larger public, the number of users increased and the market of 3D materials started to expand the production (especially for PLA) but also started to create a wider range of materials with different properties and specifications. This was also the moment when the number of the research paper on Medical cases using Additive manufacturing began increasing[1]. The process of product development is in continuous growth, updated every day by new and advanced versions of this technology that shape the future of a wide range of industries, including medical devices. The advantages of rapid prototyping using 3D printing technology exceed by far just the pragmatic aspect of cost savings[2]. In medicine, the 3D Printing Technology branched out, covering multiple areas, such as: bio-printing, tissue engineering and designed scaffold structures manufacturing[3],[4],[5], but also surgical related achievements – implants[6],[7]; surgical devices[8],[9],[10]; preoperative planning[11],[12]; prosthetics[13]. It is the experts’ opinion that the quality and innovation of new designs made a great difference in the medical field and have constantly improved, achieving great performances[2]. Advanced versions of the technology are making a major difference in the process of product development across a wide range of industries, including medical devices. And rapid prototyping using 3D printing technology provides more than just cost savings. Experts note that the quality and innovation of new designs, such as medical prosthetics, has been greatly improved.

We focused our research on the implementation of 3D printed models in complex orthopaedic cases such as: scoliosis (idiopathic, congenital and neuromuscular), hip dysplasia, femoral osteosarcoma, pelvic trauma. Another point of interest, in our study, was to analyze the properties and parameters that the 3D printed models must possess in order to be successfully used in preoperative planning. In our study, we mostly used Polylactic acid (PLA) and Polyether ether ketone (PEEK) through the means of fused deposition modelling (FDM) technology.

Being a very elaborated process, it involved a multidisciplinary team (an orthopaedic surgeon, a radiologist and an engineer) and required a work protocol, in order to accomplish the optimal criteria that allowed surgical manoeuvres to be simulated on the resulted 3D printed models.

2 MATERIALS AND METHODS

The work protocol divides in 3 sections:

1. Acquiring the DICOM images by performing a CT scan,
2. Processing the DICOM files in order to obtain the CAD model,
3. 3D Printing.

2.1 Acquiring the DICOM images

This step implies gathering imagistic acquisitions by the radiology department. Before performing the CT exam, the radiologist must be informed that the obtained data will be used to make a 3D printed model, so that he may adjust the technique to the right specific parameters required by their purpose. It is important for the CT scan to contain the whole region to be analyzed, so a single continuous CT with contiguous slices is recommended. The scan can be helical/spiral but it must be one continuous axial acquisition of entire region of interest (ROI). Slice thickness should measure under 1 mm and the slice spacing must not exceed the slice thickness. The reconstruction must be performed with Kerner B40S – soft tissue; also it's important to minimize the metal artifacts and noise by adjusting dose parameter. The images obtained at the end of this first step are DICOM files.

2.2 Processing the DICOM files in order to obtain the CAD model [14]

Using the 3D Slicer software[15], the DICOM files previously obtained are processed following these steps:

1. 3D data presentation – 3D Slicer volume rendering – default 3D reconstruction using all DICOM images,
2. Interest cropping region – extraction sub-volume including interesting bone geometry,
3. Segmentation – manual tresholding the interesting bone using Hounsfield scale,
4. Exporting stereolithography (bone geometry in .stl file format), the .stl format is a file format native to stereolithography printing[16].

The graphic representation of the 3D model is exported to an „.stl" format to suffer a „cleaning" process in the Blender 2.79[17] consisting in removing isolated parts of a mesh, non-manifold triangles, edges and vertices. In the case of a larger and more complex graphic pattern there is the posibility of turning the model into smaller segments followed by the reassembling post printing. This way provides a lower production time and also a smaller quantity of fabric required.

The result is processed in Autodesk MeshMixer[18] for the removal of isolated parts of the mesh and closing the holes due to imperfections.

2.2 3D Printing

In this final and very important stage, the parameters are adjusted to various references such as: the type of material being used, the model's level of complexity, the purpose it serves. The choice of material depends mostly on what the user wants to print, so the key decision may be taken based on the following criteria[19]: ease of printing, visual quality, max stress, elongation at break, impact resistance, layer adhesion, heat resistance (Figure 1). In our practice we use PLA or PEEK filament (2,75 mm diameter) with a 3D printer on Fused Deposition Modeling technology (FDM).

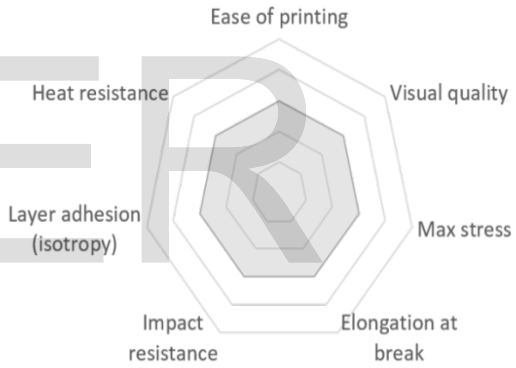

Fig. 1. A spider web graphic indicating the material properties available for comparison. Each material may be ranked following criteria on a 1 to 5 scale, where 1 is "low" and 5 is "high"[19]

Polylactic acid (PLA)

Is a biodegradable and bioactive thermoplastic aliphatic polyester derived from renewable resources. Polylactic Acid is biodegradable and has characteristics similar to polypropylene (PP), polyethylene (PE), or polystyrene (PS). PLA polymers range from amorphous glassy polymer to semi-crystalline and highly crystalline polymer with a glass transition of 60°C and melting points of 130-180°C[20]. PLA has a glass transition temperature 60–65°C, a melting temperature 173–178°C and a tensile modulus 2.7–16 MPa[21]. Heat-resistant PLA can withstand temperatures of 110 °C[22]. The basic mechanical properties of PLA are between those of polystyrene and PET[20] (Fig. 2). PLA is very rigid and actually quite strong, but is very brittle, also polylactic acid are not resistant at high heat, UV radiation or chemical substances. Based on these grounds, PLA is a great material to use in preoperative planning, process that doesn't involve sterilisation.

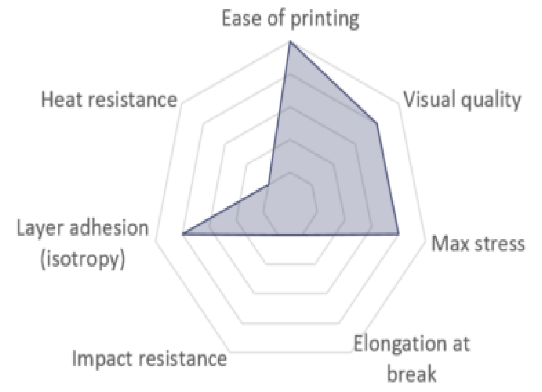

Fig. 2. The material profile of PLA.

Polyether ether ketone (PEEK)

Polyether ether ketone (PEEK) is a colourless organic thermoplastic polymer in the polyaryletherketone (PAEK) family. PEEK polymers are obtained by step-growth polymerization by the dialkylation of bisphenolate salts. Typical is the reaction of 4,4'-difluorobenzophenone with the disodium salt of hydroquinone, which is generated in situ by deprotonation with sodium carbonate. The reaction is conducted around 300 °C in polar aprotic solvents - such as diphenyl sulphone[23].

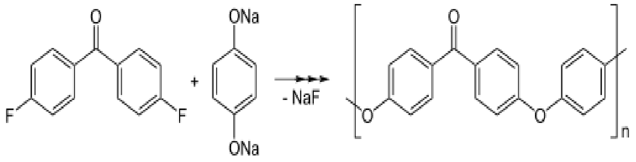

Fig. 3. Synthesis of polyether ether ketone (PEEK)

Nowadays, through the help provided by developing new technologies and new generation biocompatible materials, it is possible to recreate and even to replace more and more parts of the human body. The confirmation of biocompatibility turned PEEK materials in a suitable replacement (in specific cases) for titanium alloy, that up until the latest years was generally used[24].

Case Report

We present the case of a 50 year old woman, with severe developmental hip dysplasia - Crowe type III. Around the age of 1 y.o. the patient suffered several surgical interventions in an attempt to correct the right hip affliction. In spite of this effort, the condition progressed to secondary dysplastic coxarthrosis and femoral head subluxation (Fig. 4).

The patient's examination reveals a leg-length inequality of 3 cm and a severe limited range of motion present at the right hip. The doctors opted for a Cementless Total Hip. The model we printed for this case consists in the right coxal bone of the patient's hip, based on previous CT scans, made at a 1:1, using PLA (Polylactic acid: ($C_3H_4O_2$). Due to the complexity and size of the model, we decided to split the design in 3 segments, that we assembled post printing. This division of the 3D graphic model was made in a manner that would allow the entire acetabular cavity to be all included in one of the segments, this way enabling the reaming process to be performed in optimal conditions. In our current practice we use Wanhao Maker[25] and the next parameters: Layer Height 0.10 mm, Wall Thickness 0.80 mm, Fill Density 8 %, Speed Print 40 mm/s, Speed Travel 90 mm/s, Speed Infill 85 mm/s, Infill overlap 25%. The first model was printed with the section bearing the acetabulum in a vertical orientation, perpendicularly to the printing surface, with infill overlap 25%. The second model was printed with the acetabular cavity facing upwards with a parallel orientation against the printing surface and with an infill overlap of 35%. We performed successive reaming sessions on both of the models and both behaved properly subjected to mechanical stress, showing no sign of collateral deterioration. It is safe to say that the printed models proved a good mechanical performance. Reaming the exterior wall of the model was more difficult and of greater resistance, but in the grid infill structure, once the wall was pierced the reaming became similar to the process performed on actual bone, especially in the second model case, with 35% infill. We noticed that the model printed vertically, with infill overlap 25%, had a grid infill structure less resistant than the bone structure. The reaming process was performed with a 44mm reamer, an important note being that no friction melting phenomena occurred on any of the models. Total hip arthroplasty (THA) for severe developmental dysplasia of the hip (DDH) is a technically demanding procedure for arthroplasty surgeons due to the presence of anatomical abnormalities such as, a small, narrow femoral canal, increased anteversion, and a hypoplastic acetabulum[26],[27]. By implementing the 3D printed models in the preoperative planning we may properly prepare for the surgical approach, adapted to the patient's needs and anatomical particularities. In addition, using this technology comes with great advantages: a lower risk level of complications during surgery, a reduced amount of time spent in the O.R., a better appreciation of the size and shape belonging to the implant and, also, it has proven itself to be very useful in establishing the position and orientation of the acetabulum and the femoral components.

Following the preoperative plan, the patient underwent a Cementless Total Hip Arthroplasty with Zimmer Taperloc/Trilogy - Acetabular Shell 44 mm and femoral head 28 mm. No short or long-term complications were documented.

Conclusions

Using PLA and PEEK to print 3D models is an efficient method to fabricate high-resolution models, compatible with many medical purposes.

The process involves a multidisciplinary team and it is important to use a 3D printing protocol every time, in order to obtain the best results.

Before engaging in a 3D printing process, it is important to establish what purpose will the printed object serve, if it is going to be used only as visual support, or if it will be subjected to mechanical stress.

Using the 3D printing technology in orthopedy leads to a better understanding of the disease and of the deformity and allows a better appreciation of the anatomical abnormalities, therefore improving the treatment plan. Not only a lower rate of intraoperative risk is achieved by using this technology, but also it leads to a more competent way of explaining the pathology and the informed consent to the patient[14],[28].

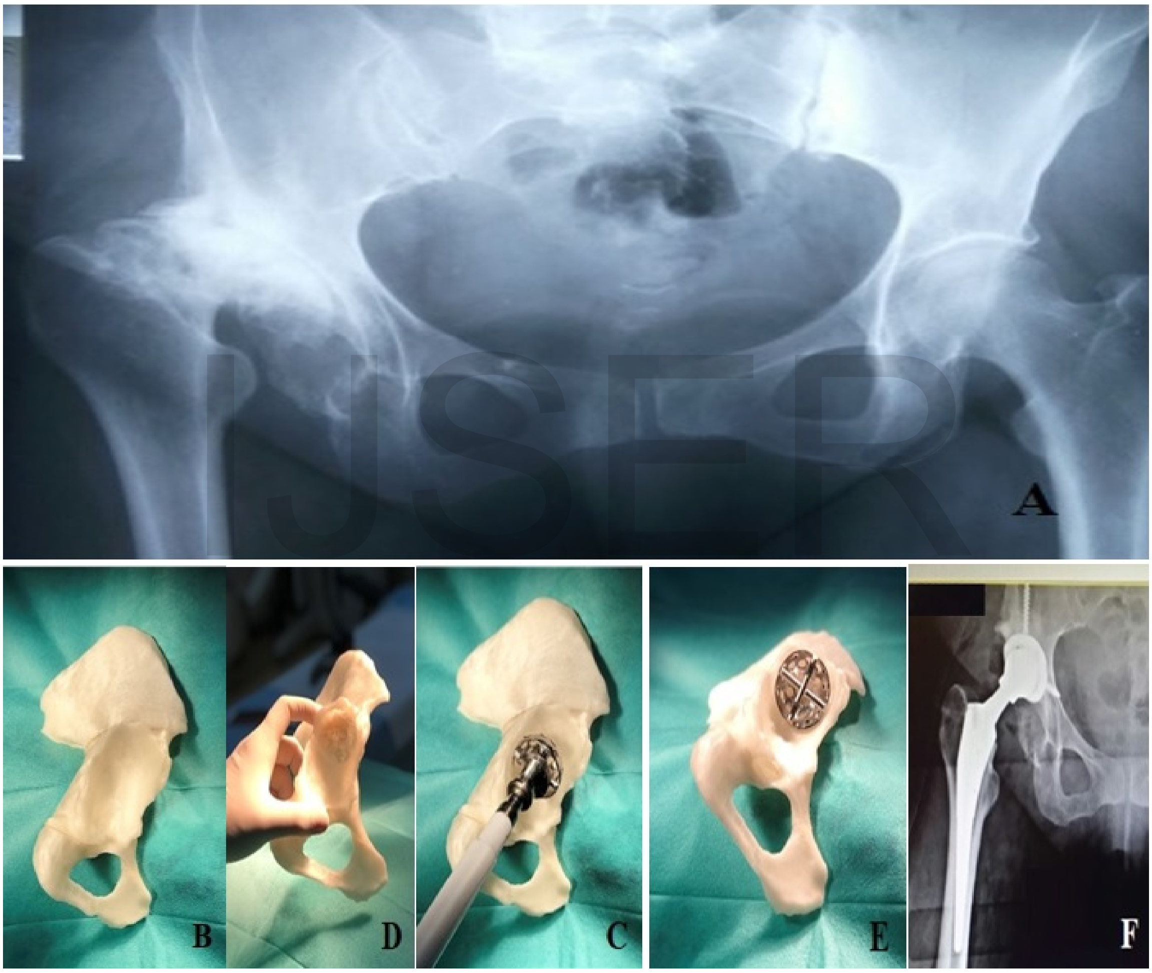

Fig. 4. Fig. 3: 3D Printed Preoperative Planning
A. Coxarthrosis secondary to congenital dysplasia; B. 3D printed coxal bone; C. Reaming the 3D printed Acetabulum;
D- E. Preoperative planning - Analyzing the location, orientation and size of the implant; F. Postoperative X-ray.

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